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Harmonization of Life Cycle Climate Performance Methodology

The IIR publishes Informatory Notes designed to meet the needs of decision-makers worldwide, on a regular basis. These notes summarize knowledge in key refrigeration-technology and refrigeration application domains. Each note puts forward future priority developmental axes and provides IIR recommendations in this context.

In 2012, the International Institute of Refrigeration (IIR) has set up a Working Group in order to assess the merits of the Life Cycle Climate Performance (LCCP) methodology.

This Informatory Note summarizes the LCCP guideline prepared by the Working Group for performing LCCP calculations of refrigeration and air-conditioning systems. It provides recommended assumptions and data sources for different types of units, presents the various existing LCCP tools and outlines usage and limitations of LCCP.

The author concludes that LCCP is a holistic metric for quantifying the environmental impacts of HVAC&R units over their lifetime and should be an essential tool in the future selection, development and implementation of these units.

This Informatory Note was prepared by Yunho Hwang, Chairman of the IIR Working Group "Life Cycle Climate Performance Evaluation" and was reviewed by several IIR experts.

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Introduction

The International Institute of Refrigeration (IIR) established a Working Group in January 2012 to assess the merits of the Life Cycle Climate Performance (LCCP) methodology [1]. The Working Group developed a guideline for performing LCCP calculations for air-conditioning and refrigeration systems with recommended assumptions and data sources for different types of units.

The developed guideline provides a harmonized method to calculate the LCCP for all types of stationary air-conditioning and heat pump systems. The process and assumptions by which LCCP should be approached are discussed. This guideline aims to provide designers, facility operators and manufacturers a way to effectively evaluate and compare the environmental impact of different systems over the course of their lifetimes.

This note summarizes the Life Cycle Climate Performance guideline. The full guideline is available on the IIR's Web site (www.iifiir.org), in the "LCCP Evaluation Working Group" Section (http://www.iifiir.org/userfiles/file/about_iir/working_parties/WP_LCCP/08/Booklet-LCCP-Guideline-V1.2-JAN2016.pdf).

Life Cycle Climate Performance

Life Cycle Climate Performance is an index by which HVAC&R systems can be evaluated for their global warming impact over the course of their lifetime. It is calculated as the sum of direct and indirect emissions generated over the lifetime of the system from "cradle to grave." Direct emissions include all effects from the release of refrigerant into the atmosphere during the lifetime of the system. This includes annual leakage and leakage during the disposal of the unit. The indirect emissions include emissions from the manufacturing process, energy consumption and disposal of the system [2-10].

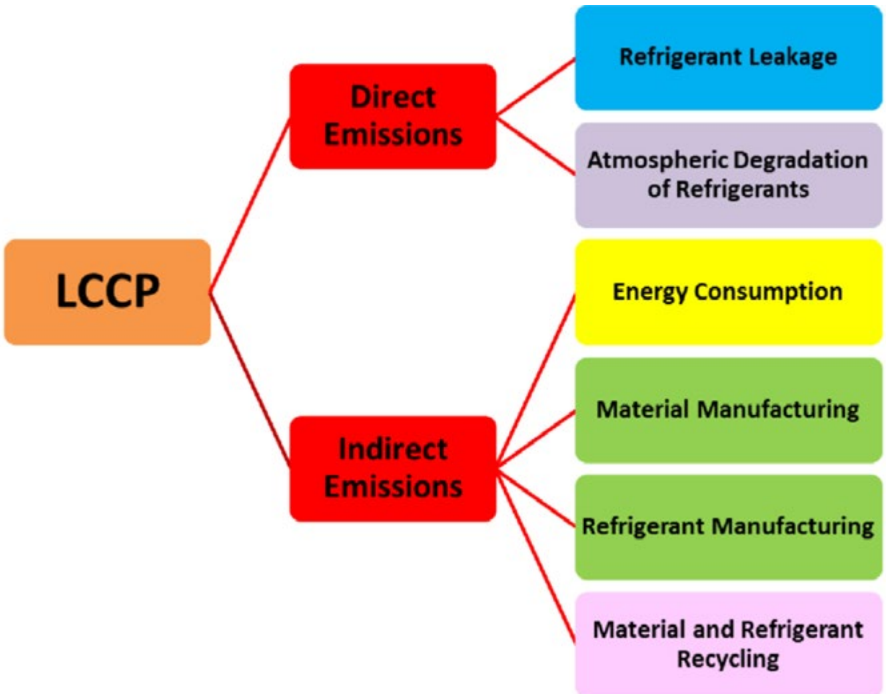

Figure 1: *Life Cycle Climate Performance Components*

1.1. LCCP Equation

The LCCP equation is split into two main parts, direct and indirect emissions, as shown in Figure 1. The resulting equations are shown in Equations (1-3). Each component accounts for a different type of emissions released over the lifetime of the unit. The emission terms are in the units of kg CO_{2e}/kg.

Equation 1: *Life Cycle Climate Performance Equation*

$$LCCP = Direct\ Emissions + Indirect\ Emissions$$

Equation 2: *Direct Emissions Equation*

$$Direct\ Emissions = C \cdot (L \cdot ALR + EOL) \cdot (GWP + Adp.\ GWP)$$

Equation 3: *Indirect Emissions Equation*

$$Indirect\ Emissions = L \cdot AEC \cdot EM + \Sigma\,(m \cdot MM) + \Sigma\,(mr \cdot RM) + C \cdot (1 + L \cdot ALR) \cdot RFM + C * (1 - EOL) \cdot RFD$$

Where:

C = Refrigerant Charge (kg)

L = Average Lifetime of Equipment (yr)

ALR = Annual Leakage Rate (% of Refrigerant Charge)

EOL = End of Life Refrigerant Leakage (% of Refrigerant Charge)

GWP = Global Warming Potential (kg CO_{2e}/kg)

Adp. GWP = GWP of Atmospheric Degradation Product of the Refrigerant (kg CO_{2e}/kg)

AEC = Annual Energy Consumption (kWh)

EM = CO_2 Produced/kWh (kg CO_{2e}/kWh)

m = Mass of Unit (kg)

MM = CO_{2e} Produced/Material (kg CO_{2e}/kg)

mr = Mass of Recycled Material (kg)

RM = CO_{2e} Produced/Recycled Material (kg CO_{2e}/kg)

RFM = Refrigerant Manufacturing Emissions (kg CO_{2e}/kg)

RFD = Refrigerant Disposal Emissions (kg CO_{2e}/kg)

1.2. Direct Emissions Data Sources

Direct emissions are comprised of the effects of refrigerant released into the atmosphere over the course of the lifetime of the unit. This includes:

- Annual refrigerant loss from gradual leaks,
- Losses at end-of-life disposal of the unit,
- Atmospheric reaction products from the breakdown of the refrigerant in the atmosphere.

These three categories are calculated using the rate of refrigerant leakage multiplied by the refrigerant charge and the global warming potential (GWP) of the refrigerant.

1.2.1. Global Warming Potential

This guide uses the GWP values obtained from the United Nations Intergovernmental Panel on Climate Change's (IPCC) Fifth Assessment: Climate Change (AR5) [11]. These values are calculated using a 100 year timeline for policy and consistency purposes. The AR5 values are the most commonly used values in research and in public policy internationally. If the refrigerant is not included in AR5, the manufacturer's GWP values may be used. To calculate refrigerant mixtures a weighted average of the component refrigerants should be used. Adaptive GWP is a GWP of atmospheric reaction products of refrigerant [12]. The value should be included in the calculation when available. Table 1 shows several common refrigerant GWP and Adaptive GWP values.

Table 1: *Refrigerant Information*

Refrigerant	GWP [3, 11] (kg CO_{2e}/kg)	Adaptive GWP (kg CO_{2e}/kg)
Ammonia	0	0
CO_2	1	0
HFC-32	677	Not available
HFO-1234yf	< 1	3.3 [12]
HFC-134a	1,300	1.6 [12]
HC-290	3	Not available
HFC-404A	3,943	Not available
HFC-410A	1,924	Not available

1.2.2. System Information

Average unit lifetimes (L), unit annual refrigerant leakage rates (ALR) and end-of-life leakage rates (EOL) are taken from AR4, AR5 reports and United Nations Environment Programme (UNEP) Technical Options Committee 2002 report [11, 13-14]. The values given are the averages for developed countries and include those units already in service. Annual leakage rates are the sum of the gradual leakage of a system over the course of a year. These averages also include catastrophic leaks spread out over the lifetime of the unit. This term does not include refrigerant lost when the unit is disposed of. The values are displayed in Table 2 for various types of units. The end-of-life leakage rates include the amount of refrigerant that is lost when the unit is disposed of. These rates reflect regulations passed in developed countries to limit the amount of refrigerants that are released into the atmosphere.

Table 2: *System Information*

System Type	ALR (%)	EOL (%)	L (years)
Residential Packaged Units [2, 11]	2.5	15	15
Residential Split Units [2, 11]	4	15	15
Packaged Refrigeration [2, 11]	2	15	15
Supermarket - Direct System [2, 8, 11]	18	10	7-10
Supermarket - Indirect System [2, 8, 11]	12	10	7-10
Commercial Refrigeration - Stand Alone [11, 13, 14]	5	15	15
Commercial - Packaged Units [11, 13, 14]	5	15	10
Commercial - Split Units [11, 13, 14]	5	15	10
Chillers [11, 13, 14]	5	15	15
Marine [11, 13, 14]	20	15	15

1.3. Indirect Emissions Data Sources

Indirect emissions result from the use of the unit during its lifetime and the manufacturing and disposal of its components. It includes:

- Emissions from electricity generation,
- Emissions from the manufacturing of materials,
- Emissions from the manufacturing of refrigerants,
- Emissions from the disposal of the unit.

1.3.1. Energy Consumption Calculation

The emissions generated from energy consumption are the largest factor in the LCCP equation. The preferred method to calculate the Annual Energy Consumption of the system is to use an Annual Load Model in accordance with ASHRAE, AHRI, and ISO standards [15-16]. Two Excel tools were built for the IIR guideline booklet and can be found on their website [1]. Another Excel tool is also available through AHRI for more complex comparisons of residential units [3].

The cooling and heating loads should be calculated using the correct International Organization for Standardization (ISO) Standard [17] or ANSI/AHRI Standard for the type of system being evaluated. Most of the standards are available in SI and IP units. For air-conditioning, heating, refrigeration units and chillers whose performance is dependent on ambient weather conditions, a minimum of four temperature bins for cooling and four bins for heating should be used. The load should be calculated for each bin and then summed to determine the total energy consumption per year. For units whose energy consumption is not dependent on ambient weather conditions, the calculation procedure in the respective standard should be used and summed for the unit's lifetime. Once the total energy consumed is calculated this should be multiplied by the electricity generation emissions rate for the area.

Standby power or compressor crankcase heaters may also consume a significant amount of energy. These devices should be considered in climates where the compressor is off or in standby for a significant amount of time.

The baseline equation as written assumes that the system is recharged to its optimal refrigerant charge annually and the effects to the energy consumption on the system are minimal. However, it is known that refrigerant leakage will have a negative impact on the performance of HVAC&R units over its lifetime. This performance degradation may be considered when calculating the energy consumption of the unit. The performance degradation can be determined using unit test data or from previous research.

1.3.2. Climate Data

The climate data is used to determine the load on the unit. This data should be broken down by hours through the year. Each hour should reflect the average over the course of a number of years. This method eliminates out irregularities from year to year. The International Weather for Energy Calculations datasets (IWEC), 2013 and the National Renewable Energy Laboratories (NREL) – Typical Meteorological Year database (TMY3), 2015 [18-22] should be used whenever possible. The International Energy Agency (IEA) and the US Department of Energy (DOE) provide lists of alternative sources if the location being modeled is not included in the IWEC datasets or TMY3 [23].

1.3.3. Electricity Generation Emissions

The emissions created by the generation of electricity are the primary factor in the LCCP calculation. Emissions rates should be measured in kg CO_{2e}/kWh. The LCCP methodology assumes that the unit being evaluated uses the electric grid for 100% of the required power. The North American Electricity Reliability Corporation (NERC) and the IEA provide current electrical power generation emissions [24-25]. The emission rate chosen depends on the purpose of the calculation. For a specific user who wants to minimize a specific application's emissions, the local rates can be used. In general, it is relevant to use a common rate over an area where the electrical networks are interconnected.

1.3.4. Material Manufacturing Emissions

Material manufacturing emissions were gathered from various industry sources in the United States and the European Union. These sources included trade associations, governmental departments, and previous research efforts. The four most common materials in the manufacture of HVAC&R units are included in the LCCP guideline. The resulting values are shown in Table 3.

1.3.5. Recycled Material Manufacturing Emissions

Many materials today are manufactured with a mixture of virgin and recycled materials. The average values for recycled materials are shown in Table 3. The emissions values for recycled materials were then taken and weighted to develop the mixed manufacturing emissions shown in Table 3 [26, 28, 30-34].

Table 3: *Material Manufacturing Emissions*

Material	Virgin Manufacturing Emissions (kg CO_{2e}/kg)	Percentage of Recycled Materials in Mixed Materials	100% Recycled Material Manufacturing Emissions (kg CO_{2e}/kg)	Mixed Manufacturing Emissions (kg CO_{2e}/kg)
Steel	1.8 [26]	29% [26, 30]	0.54 [26, 30]	1.43 [30]
Aluminum	12.6 [27]	67% [31, 32]	0.63 [31, 32]	4.5 [31]
Copper	3.0 [28]	40% [28]	2.46 [28]	2.78 [28]
Plastics	2.8 [29]	7% [33, 34]	0.12 [33, 34]	2.61 [29, 33, 34]

1.3.6. Refrigerant Manufacturing Emissions

Refrigerant manufacturing emission rates are shown in Table 4 for several common refrigerants. These values were gathered from various studies and manufacturer's information [6, 34-37]. These values are averages of the available sources.

Table 4: *Refrigerant Manufacturing Emissions*

Refrigerant	Manufacturing Emissions (kg CO_{2e}/kg)
HFC-32	7.2 [6, 36]
HFO-1234yf	13.7 [37]
HFC-134a	5.0 [35, 37]
HC-290	0.05 [37]
HFC-404A	16.7 [6]
HFC-410A	10.7 [38]

1.3.7. End-of-Life Emissions

The final component accounted for in the indirect emissions is the emissions generated by the disposal of the unit. Material disposal emissions include all emissions up to the production of recycled material. For metals and plastics this includes the shredding of the material [6, 30, 39]. For refrigerants, this includes energy required to recover the refrigerant. These emissions may be included in the manufacturing emissions if the material is produced from recycled materials. A public records search was conducted to determine the amounts of emissions generated by shredding metals and plastics. The values of 0.07 kg CO_{2e}/kg for metal and 0.01 kg CO_{2e}/kg for plastics were selected from the available sources.

Life Cycle Climate Performance Tools

2.1. LCCP Tools

Table 5 lists the available tools and their applications. The AHRI tool and IIR tools are for residential heat pumps. The ORNL tool can be used for all applications. The GREEN-MAC-LCCP tool is for mobile air-conditioning units only. TEWI can be used if a quick comparison is desired. For a more detailed evaluation LCCP should be used.

Table 5: *LCCP Tools*

Tool	Program Type	Application
AHRI LCCP	Excel Based	Single-Speed Compressor Residential Heat Pumps
ORNL LCCP	Open Source (Web and Desktop versions)	All types
GREEN-MAC-LCCP	Excel Based	Mobile Air Conditioning
IIR LCCP	Excel Based	Single-Speed Compressor Residential Heat Pumps

Usage and Limitations of Life Cycle Climate Performance

3.1. Usage of LCCP

The LCCP methodology is a very flexible tool that can be tailored for use with any type of stationary refrigeration, air-conditioning, and heat pump systems using the vapor compression cycles powered by electricity from the electricity grid. Different systems can be compared when all of the calculations use the same assumptions and calculation method as presented. This methodology should be used to compare different options in an effort to reduce the total emissions of the unit over its lifetime.

3.2. Usage of LCCP with Advanced Cycle Options and Low-GWP Refrigerants

In order to meet energy consumption reduction goals such as those proposed by the US DOE to reduce residential energy consumption by 40% from 2010 levels by 2025 [40], a combination of advanced cycle options and low-GWP refrigerant are necessary. Several advanced cycle options were applied to LCCP for a residential heat pump using R-410A including a suction line heat exchanger cycle, an expander cycle, an ejector cycle and a vapor-injection flash tank cycle. Of the cycles modeled, the best performing cycle was the vapor-injection flash tank cycle. The cycle demonstrated a reduction in LCCP of 8.2% in Atlanta, GA. When low-GWP refrigerants were applied to the cycle the LCCP reduction was further enhanced. A vapor-injection cycle in Atlanta, GA, using a refrigerant with a GWP of 10, saw a reduction in LCCP of 17.8%.

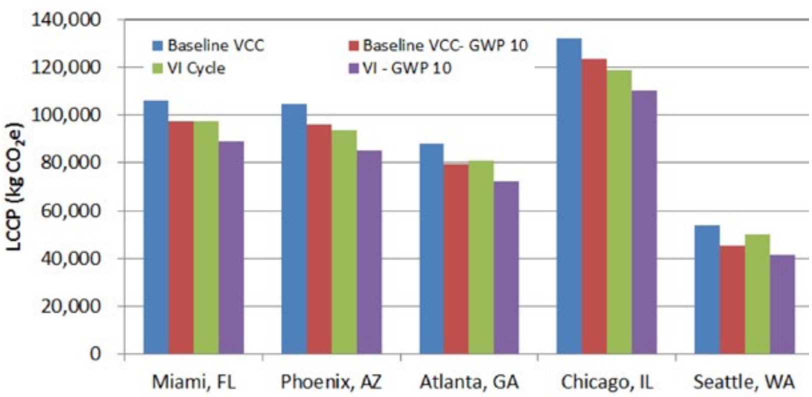

Figure 2: *Advanced Cycle and Low-GWP Refrigerant Comparison*

3.3. Limitations of LCCP

Like for TEWI, LCCP calculations are dependent on a number of assumptions about the system performance, manufacturing emissions, typical system characteristics, and energy generation emissions. These values are all subject to a certain amount of uncertainty. LCCP should be used as a comparison tool for systems with similar performance and function. It is not intended to be used as a definitive estimate of lifetime emissions. Small variations between different units may not have significance because of the inherent uncertainty in the assumed emission values.

Nomenclature

Adp. GWP	Adaptive GWP
AEC	Annual energy consumption
ALR	Annual leakage rate (% of refrigerant charge)
C	Refrigerant charge
CO_{2e}	Equivalent to CO_2
L	Average lifetime of equipment
LCCP	Life Cycle Climate Perfomance
EM	CO_{2e} produced per unit kWh of electricity
EOL	End of life refrigerant leakage
GWP	Global Warming Potential
m	Mass of unit
MM	CO_{2e} produced per unit mass of material
mr	Mass of recycled material
RFM	Refrigerant manufacturing emissions
RFD	Refrigerant disposal emissions
RM	CO_{2e} produced for unit mass of recycled materia

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Recommendations

- **LCCP Usage**. LCCP is a holistic metric for quantifying the environmental impacts of HVAC units. It is an easily understood method for comparing the effects of these units over their lifetime. This metric should be an essential tool in the future selection, development and implementation of these units.
- **Comparing Different Refrigerants with LCCP**. When comparing different refrigerants, the refrigeration capacities of the refrigerants should be considered. If necessary, the capacities should be weighted so refrigerants can be more accurately compared.
- **LCCP Tools**. There are several LCCP tools in existence. Table 5 lists the available tools and their applications. The AHRI tool and IIR tools are for residential heat pumps. The ORNL tool can be used for all applications. The GREEN-MAC-LCCP tool is for mobile air-conditioning units only. TEWI should be used if a quick comparison is desired. For a more detailed evaluation LCCP should be used.
- **LCCP Reduction**. There are two general pathways to reduce LCCP of HVAC units, reduction of energy consumption and the use of low-GWP refrigerants. Advanced cycles are an effective way to reduce energy consumption of the unit. In combination with low-GWP refrigerants, LCCP can be greatly reduced. However, a greater effort is needed to significantly improve the energy efficiency in order to meet the goals set by the Paris Agreement at the climate conference (COP21) in December 2015.
